

International Journal of Modern Physics C  
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## PROTO-NEUTRON AND NEUTRON STARS

V. Dexheimer

*FIAS, Johann Wolfgang Goethe University, Ruth-Moufang-Str. 1, 60438 Frankfurt am Main,  
 Germany  
 dexheimer@th.physik.uni-frankfurt.de*

S. Schramm

*CSC, FIAS, Johann Wolfgang Goethe University, Max-von-Laue-Strae 1, 60438 Frankfurt am  
 Main, Germany*

H. Stoecker

*FIAS, ITP, Johann Wolfgang Goethe University, Ruth-Moufang-Str. 1, 60438 Frankfurt am  
 Main, Germany*

Received Day Month Year

Revised Day Month Year

The parity doublet model, containing the SU(2) multiplets including the baryons identified as the chiral partners of the nucleons is applied to neutron stars. The maximum mass for the star is calculated for different stages of the cooling taking into account finite temperature/entropy effect, trapped neutrinos and fixed baryon number. Rotation effects are also included.

*Keywords:* chiral symmetry — parity doublet model — neutron stars — cooling — rotation

PACS Nos.: 11.25.Hf, 123.1K

### 1. Introduction

It has been shown that effective chiral hadronic models can satisfactorily describe nuclear matter, properties of finite nuclei as well as the structure of neutron stars<sup>1</sup>. While most of the approaches are based on variations of the linear sigma model or its non-linear realization, in the approach discussed here the scalar sigma meson serves to split the nucleon and its chiral partner (particle with opposite parity), while in the chirally restored phase both baryonic states become degenerate but not massless. The presence of the chiral partner allows to have a bare mass term  $m_0$  in the Lagrangian density in such a way that it does not break chirality because the physical fields in this case are a mixture of the fields of the particles and their chiral partners<sup>2,3,4</sup>.

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## 2. The parity Doublet Model

It is assumed that the star is in chemical equilibrium and the baryons interact through the mesons  $\sigma$ ,  $\omega$  and  $\rho$  (included in order to reproduce the high asymmetry between neutrons and protons). Electrons are included to insure charge neutrality. The Lagrangian density in mean field approximation becomes

$$L_{MFT} = L_{kin} + L_{Bscal} + L_{Bvec} + L_{vec} + L_{scal} + L_{SB}, \quad (1)$$

$$L_{Bscal} + L_{Bvec} = - \sum_i \bar{\psi}_i [g_{i\omega} \gamma_0 \omega^0 + g_{i\rho} \gamma_0 \tau_3 \rho^0 + M_i^*] \psi_i, \quad (2)$$

$$L_{vec} = -\frac{1}{2}(m_\omega^2 \omega^2 + m_\rho^2 \rho^2) - g_4[\omega^4 + 6\rho^2 \omega^2 + \rho^4], \quad (3)$$

$$L_{scal} = \frac{1}{2} \mu^2 \sigma^2 - \frac{\lambda}{4} \sigma^4, \quad (4)$$

$$L_{SB} = m_\pi^2 f_\pi \sigma,$$

where besides the kinetic term for the fermions there are terms of interaction between the baryons and the scalar and vector mesons, self-interaction terms for the vector and scalar mesons and an explicit symmetry breaking term included in order to reproduce the masses of the pseudo-scalar mesons.

The effective masses of the nucleons and their chiral partners reproduce their measured values at low densities, when the scalar condensate has its vacuum value, and they go to a specific value  $m_0 = 790$  MeV (chosen in order to have a physical compressibility at saturation<sup>5</sup>) at high densities, when the scalar condensate go to zero

$$M_\pm^* = \sqrt{\left[ \frac{(M_{N_+} + M_{N_-})^2}{4} - m_0^2 \right] \frac{\sigma^2}{\sigma_0^2} + m_0^2} \pm \frac{M_{N_+} - M_{N_-}}{2} \frac{\sigma}{\sigma_0}. \quad (5)$$

A possible, but not definite, candidate for the nucleon chiral partner is the  $N_-(1535)$ , but besides that, the case with  $N_-(1200)$  is included to study the effect of the mass of the  $N_-$ . This variation has drastic consequences on the results. For this model, four different cases first studied in <sup>4</sup> are applied to proto-neutron and neutron stars:

- P1:  $M_{N_-} = 1200\text{MeV}$  and  $g_4 = 0$
- P2:  $M_{N_-} = 1200\text{MeV}$  and  $g_4 = 200$
- P3:  $M_{N_-} = 1500\text{MeV}$  and  $g_4 = 0$
- P4:  $M_{N_-} = 1500\text{MeV}$  and  $g_4 = 200$

As will be shown, the results are also very sensitive to the value of the coupling constant of the self-interaction of the vector mesons  $g_4$ .

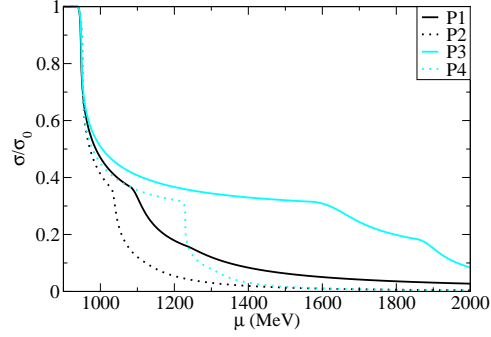


Fig. 1. Scalar condensate as a function of chemical potential for different configurations

### 3. Neutron Stars

For the parity model, when the density increases, the protons, the neutron and the proton chiral partners appear, respectively. Since the matter is not symmetric, in general the two isospin states of the chiral partner appear at different densities, which induces the chiral restoration to happen earlier compared with the symmetric nuclear matter case. As can be seen from Fig.1 the scalar condensate used in this case as the order parameter for the chiral restoration shows that this transition happens very smoothly, and can be identified as a crossover for all cases. This effect is caused by the introduction of beta equilibrium and charge neutrality. It can also be seen in this plot that for  $P3$  the chiral restoration caused by the appearance of the chiral partners happens at very high densities, beyond the ones possible inside a neutron star.

The maximum mass of the star is calculated solving the TOV equations and it shows that higher maximum values are reached for  $g_4$  equal to zero (Fig.2). That means that when  $g_4$  increases, the value of the vector meson  $\omega$  related to it decreases its value and consequently its repulsive effect, in such a way that the star can hold smaller quantity of mass against collapse. Besides the EOS for the dense part of the star, the EOS for an outer crust, an inner crust and an atmosphere have been added<sup>6</sup>.

### 4. Cooling

To study the cooling of such complex system two different features are taken into account separately: finite entropy per baryon and lepton number. The reason for considering finite entropy instead of temperature comes from the fact that in this case the temperature is higher in the center of the star and colder at the edge, which is more realistic than assuming the whole star at equal temperature. The maximum mass of the star is higher for higher entropies because the thermal effects make the EOS stiffer.

Trapped neutrinos with a chemical potential  $\mu_\nu$  are included by fixing the lepton

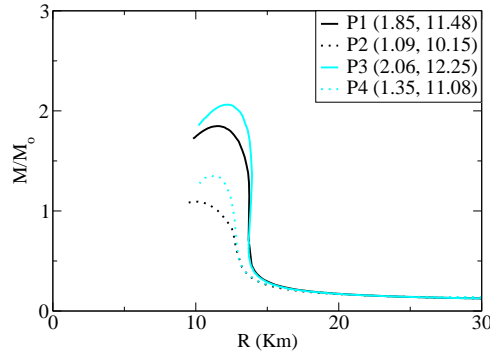


Fig. 2. Star mass as a function of radius for different configurations

number defined as  $Y_l = (\rho_e + \rho_{\nu_e})/\rho_B$ . In consequence there will be a large number of neutrinos in the star but also an increased electron density. Therefore, demanding charge neutrality, the proton density increases. For the configurations with  $g_4 \neq 0$ , the high proton fraction delays the appearance of the proton chiral partner and for having less degrees of freedom the EOS becomes stiffer. For the configurations with  $g_4 = 0$ , the chiral partners appears smoothly not having much effect, so the only effect in this case is that the high proton fraction makes the star more isospin symmetric and thus the Fermi energy smaller and the EOS softer.

These two features can be put together to describe the evolution of the star. After the supernova explosion, the star is still warm so the entropy per baryon is fixed to  $S = 2$  (the temperature increases from 0 at the edge up to 45 MeV in the center). The star still contains a high abundance of neutrinos that were trapped during the explosion so the lepton number is fixed to  $Y_l = 0.4$ . After 10 to 20 seconds the neutrinos can escape and beta equilibrium is established. After about one minute the temperature of the star has dropped below 1 MeV and the entropy per baryon can be considered zero. As it can be seen in Fig.3 and Fig.4, the effect of entropy and lepton number together is complicated. In the cases with finite  $g_4$  (P2 and P4) the star's maximum mass decreases with time while in the case with  $g_4$  equal to zero (P1 and P3), the star's maximum mass increases with time.

The problem is that this calculation does not take into account that the baryon number cannot change with time, otherwise the star would collapse into a black hole<sup>7</sup>. If the baryon number is fixed the maximum masses for every configuration decrease with time. This maximum masses with fixed baryon numbers are represented with dots in Fig.3 and Fig.4.

## 5. Rotation

The maximum frequency with which a star can rotate without starting to expel matter on the equator, named Kepler frequency, has been determined by including monopole and quadrupole corrections to the metric due to the rotation and solving

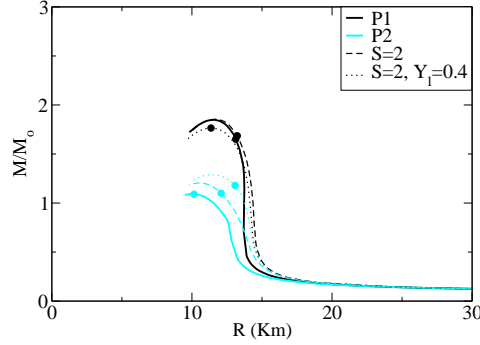


Fig. 3. Star mass as a function of radius for different stages of the cooling for the configurations with  $M_{N_-} = 1200$  MeV

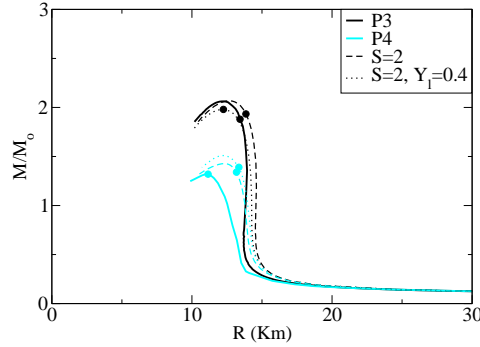


Fig. 4. Star mass as a function of radius for different stages of the cooling for the configurations with  $M_{N_-} = 1500$  MeV

the self-consistency equation for  $\Omega_K$  as it was derived in <sup>8</sup>. The rotation of the star generates a modification of the metric and the higher the rotational frequency, the higher is the mass and radius of the star<sup>9</sup>. For the different sets of parameters the increase in the maximum masses of the stars from  $\nu = 0$  to  $\nu = \nu_K$  fixing the baryon number to the value for zero frequency is of smaller than 5% (Fig. 5), different from the 15% mass increase for the case that the baryon number is not fixed. But this situation can be identified as the spin down of a cold star with a certain baryon number that continues until it emits all its energy and stops rotating. At this point the star is considered “dead”.

## 6. Conclusion

With increasing density .i.e. toward the center of the star, chiral partners appear, reaching a point where they exist with about the same densities as the corresponding nucleons. The decrease in the scalar condensate signals the restoration of the chiral

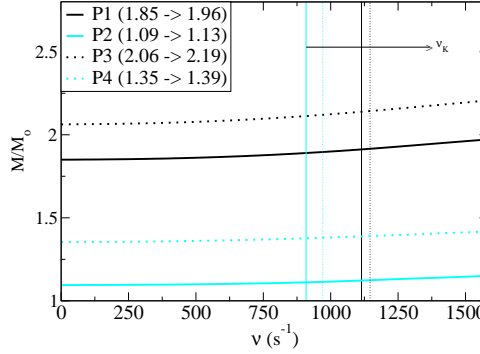


Fig. 5. Star mass as a function of rotational frequency for different configurations

phase. This transition is a cross over for any of the studied configurations due to the requirements of beta equilibrium and charge neutrality.

The maximum mass of the star is higher when the coupling constant  $g_4$  is set to zero (P1 and P3) although these values have to be constrained to a fixed baryon number during the different stages of the evolution - the constraint given by the warm case with trapped neutrinos for  $g_4 = 0$  and for the cold beta equilibrium case for  $g_4 \neq 0$ . In this way, the maximum mass and radius of the star decrease with time. A separate analysis shows that the mass and radius of the star increase when rotation is included. A study of cooling effects in the first seconds of the neutron star life together with rotation and angular momentum conservation is currently under investigation.

## References

1. P. Papazoglou, D. Zschesche, S. Schramm, J. Schaffner-Bielich, H. Stoecker and W. Greiner, Phys. Rev. C **59** (1999) 411.; S. Schramm, Phys. Lett. B **560** (2003) 164; S. Schramm, Phys. Rev. C **66** (2002) 064310.
2. C. DeTar and T. Kunihiro, Phys. Rev. D **39**, 2805 (1989).
3. D. Jido, Y. Nemoto, M. Oka and A. Hosaka, Nucl. Phys. A **671**, 471 (2000) [arXiv:hep-ph/9805306].
4. D. Zschesche, L. Tolos, J. Schaffner-Bielich and R. D. Pisarski, Phys. Rev. C **75** (2007) 055202 [arXiv:nucl-th/0608044].
5. V. Dexheimer, S. Schramm and D. Zschesche, arXiv:0710.4192 [nucl-th].
6. G. Baym, C. Pethick and P. Sutherland, Astrophys. J. **170**, 299 (1971).
7. T. Takatsuka, Nucl. Phys. A **588**, 365 (1995).
8. N. K. Glendenning and F. Weber, Phys. Rev. D **50**, 3836 (1994).
9. S. Schramm and D. Zschesche, J. Phys. G **29**, 531 (2003) [arXiv:nucl-th/0204075].